INVESTIGATING THE RELATION BETWEEN COMMON CAUSE COUPLING FACTORS AND AGEING

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Abstract

Usually, probabilistic safety analyses are using the assumption of the constant component failure rate, and the assumption that the probability associated to common cause failure (CCF) will be constant in time. Still, as ageing phenomena could have some influence on components or systems performances, is probable that it could influence the probability of occurrence of CCFs also. This paper is devoted to investigation of the most important CCFs initiating factors from point of view of relation to ageing phenomena. The connections between CCF potential and ageing phenomena, as the influence of the individual prevention factors against CCF were evaluated. A questionnaire has been developed on this topic and all the inputs provided were summarized, compared and commented. The analysis has not been limited only to the list of negative factors that would increase the CCF potential, it has included also positive factors representing the prevention and correction measures applied with the aim to avoid occurrence and recurrence of CCF events, whether related to ageing or not. Two main topics were discussed: a) the strength of relation between the individual CCF coupling factors (contributing to total CCF potential) and ageing phenomena; b) the effect of CCF prevention measures on the coupling factors versus ageing relation (estimated for those CCF coupling factors that were evaluated as coincident with ageing phenomena, with at least medium level of coincidence).

Keywords: *coupling factors, common cause failures, ageing phenomena*

Introduction

In the last years, it was acknowledged that the probabilistic safety analyses (PSA) tools have been reached a certain level of maturity, and PSA results can bring important issues to successfully complement deterministic analyses. Common cause failures (CCF) analysis has been an integral part of PSA scope for nuclear power plants for many years now [1], [2].

Since plant systems are normally equipped with several mutually redundant trains, the probability of multiple failures having the same cause of failure cannot be overlooked, and in some cases, these multiple failures occurring at the same time (or after some small time shift) are representing the systems susceptibility to potential loss of function.

For the purpose of CCF analysis, the components cannot be judged alone, and they should be grouped. CCF groups include the components of the same type belonging to redundant trains of the same system (modelling of inter-system residual dependencies is very rare in current PSA studies, although some plant specific experience may support this modelling).

Common cause failure groups [3] can be established using the systematic searching for common points in design and operation, particularly related to the following items: service conditions; design or manufacturer attributes; environment characteristics; maintenance activities. The search for common points (as they represent aspects of possible CCF potential) is done systematically, in sufficient level of detail, using a checklist. The checklist for CCF identification is usually supplemented by plant walk-downs.

The traditional probabilistic safety analyses are considering as true the assumption of the constant failure rate for components, as the assumption that the probability associated to common cause failure will be constant in time. Still, as ageing phenomena could have some influence on components or systems performances, it is probable that it could influence the probability of occurrence of common cause failures also.

In case of ageing phenomenon, it is well known that some components are ageing much faster than the others and the failure potential spectrum is changed once more over components types, as soon as combined effect of independent failure causes, CCF coupling factors and ageing is taken into consideration.

The effects of ageing could be multiple and variable. On system availability level, ageing could induce the modification of system success criteria, could increase the CCF probability for highly redundant systems, and could change the list of contributors to overall system unavailability. On overall plant level, ageing could induce the modification of initiating event frequencies, the probability of mitigation of undesired events (probability of unavailability for safety systems), the occurrence of inter-systems CCF, the dominant sequences, and could change the list of major contributors to the accident sequences.

In case of CCF, the individual independent failure potential is further combined with different strength of coupling factors effects, making the spectrum of failure potential to be distributed in different ways than the case when the ageing was not considered.

The potential relation between common cause failures and ageing phenomena was studied [4] in the framework of EC JRC Ageing PSA (APSA) project, network dedicated to investigation of ageing effects using PSA studies. It is intended that the resulting knowledge from the project running will help PSA developers and users to efficiently incorporate the effects of equipment ageing into current PSA tools and models.

Summarizing, APSA expected results are the following:
- Contributions to a better understanding of important issues in modelling of ageing phenomena using PSA models;
- Developed set of feasible approaches/models and methodological guidelines;
- Proved feasibility of the proposed approaches/models by case studies results;
- Provided support & training for correct application of the project methodological guidelines.

Ageing phenomena connections with common cause failures coupling factors

When CCF occurrence potential become effective (at some moment of time), it leads to multiple components failures (the initial failure is expanding to further components). In the reliability and risk analyses, common cause failures may be seen as a result of combination of two phenomena:
- occurrence of the triggering event, which is leading to the unavailability of one component
- existence of conditions for failure coupling (presence of common cause coupling factors), leading to loss of more redundant components of the same type and function.

The symptoms of these two factors can be searched for in the operational records of NPP events. Both these issues, which form common cause failure together, may be related to ageing, having in coincidence or independent relations.
The relation to ageing of the triggering event may be solved in detailed analyses of data records (records related to independent failures) and may be addressed in the basic component ageing models.

The total level of CCF potential, particularly the first failure potential to expand to other components also, is not limited to the presence of common cause coupling factors, it depends also on the quality and strength of adopted strategy for CCF prevention. For most of the factors that initiate the occurrence of CCF events, elements of prevention and defence of common cause failures, having the defined role to limit the CCF potential, can be defined as well. Similar to the coupling factors, these anti-CCF factors can be investigated from point of view of connection with ageing also.

As a consequence, analysis of link between CCF events and ageing should consist of two parts - analysis of CCF coupling factors over time and parallel analysis in time of prevention and defence factors.

CCF coupling factors are divided into three basic categories, [5]: a) hardware based coupling factors; b) operational based coupling factors; c) environmental based coupling factors.

The identical design and physical characteristics of the components may propagate failure mechanisms among several components, and they constitute the so-called hardware based coupling factors. They may be divided in two subcategories: hardware design category and hardware (manufacturing and installation) quality category.

The design-related hardware couplings may be considered at system level and component level. System level coupling factors include features of the system (or groups of components), external to the components, that might cause the propagation of failures to more than one component. At component level, the coupling factors include features within the boundary of each component.

The hardware design category includes the following coupling factors, [5]:
▪ *same physical appearance* – describes the cases where several components have the same identifiers (colour, size, shape, code - letter or number), which may lead to components misidentification by the operating or maintenance staff
▪ *system layout/ configuration* – refers to the arrangement of components that form a system
▪ *same component internal parts* – is referring to the case when several components may fail because of the failure of similar internal parts or subcomponents
▪ *same maintenance/ test/ calibration characteristics* – are related to the similarity in maintenance/ test/ calibration requirements, including frequency, type, techniques, and required level of expertise for the personnel involved.

The hardware quality coupling factors are referring to characteristics introduced as common elements for the quality of hardware, and include, [5]:
▪ *manufacturing attributes* – is referring to the same manufacturer, same manufacturing method, same material and same quality control procedure

▪ *construction/ installation attributes* – refers to the same construction/ installation staff, construction/ installation procedure, same construction / installation / testing verification procedure.

The coupling factors allowing the propagation of failure mechanisms due to the existence of identical operational characteristics among several components are called the operational-based coupling factors. These include [5]:
▪ *same operating team* - refers to the events that may happen, if the same operator (team of operators) is assigned to operate all trains of a system. In this case, we have an increased probability that one operator error will affect multiple components simultaneously
▪ *same operating procedure* - refers to the cases when operation of identical (functional or physical) components is governed by the same operating rules; as a direct consequence, any deficiency in the common procedure could induce failures of all these components.
▪ *same maintenance/ test/ calibration team* - refers to the case when the same (maintenance/ test/ calibration) team is in charge of maintenance/ test/ calibration activities performed on multiple components
▪ *same maintenance/ test/ calibration procedures*

Since it is considered as impractical to develop and implement diverse procedures for non-diverse equipments, the common procedures could be responsible for multiple failures occurrences, due either to procedural errors, or to wrong interpretation of procedural steps.

The coupling factors that propagate failure mechanisms on account of identical environmental characteristics are named environmental-based coupling factors and include:
▪ *same plant location* - refers to exposure of all redundant components to the same environmental stresses, because of the same plant location (flood, fire, high humidity, earthquake)
▪ *same component location* - refers to exposure of multiple components to similar environmental stresses, because of their concrete location (vibration, failure of ventilation systems, heat generated by other components).
▪ *internal environment/ working medium* - is related to use of the same operating medium by multiple components. Operating with the same dirty water, for example, could cause multiple failures due to corrosion.

Connections between components ageing and common cause failures should be seen as one specific topic of ageing treatment in the PSA study.

The main goals of the analysis was to study the most important common cause failures initiating factors (CCF coupling factors) [6] from point of view of their relation to ageing phenomena. The study included two parts: one dedicated to analysis of plant operating experience and the other one to performing a qualitative analysis. The qualitative analysis part had as objective to investigate and to estimate the most important CCFs coupling factors from point of view of their relation to ageing phenomena. The efforts included the steps:
• specification of spectrum of contributors representing CCF potential and CCF prevention factors
• study and discussion of ageing impact on the CCF coupling factors
• discussion on the impact of ageing phenomenon on prevention factors.

Analysis of plant operational experience part had as objective to find evidence about relation between CCFs and ageing mechanisms, and it included as steps:
• investigation of operational experience records, for any event which may be seen as CCF and, at the same time, as consequence of ageing mechanisms influence
• analysis of examples of CCF events taken from real plant experience regarding any possible relation to ageing (to support or not the conclusions made during the first part of the analysis).

A questionnaire has been developed on this topic and all the inputs provided (developed in completely independent way) were summarized, compared and commented. The structure of factors analysed corresponded to the typical schemes of CCF potential contributors, as identified and classified in the methodologies used in CCF analyses (qualitative and quantitative), [5, 6].

The analysis has not been limited only to the list of factors that would increase the CCF potential, it has investigated the influence of positive factors (representing prevention measures applied with the aim to avoid occurrence of CCF events, whether related to ageing or not) also.

The following list of items, similar to checklist used in searching for CCF vulnerability [5], was used: *component type* (motor operated valve, pump, circuit breaker, etc.), including any special design / construction characteristics; *component manufacturer*, *component function* (system isolation, measurement, electric power supply); *component boundaries and system interfaces*; *component visual similarity and corresponding supporting factors* (location in the same room/ building, similar parts, identical control panels, similar tables with component identification data); *internal conditions* (pressure, temperature, flow, chemistry and radioactivity characteristics, voltage); *environmental conditions* (temperature, humidity, pressure); *component common status conditions and operating characteristics* as normally closed/open, running, stand-by; *testing and maintenance procedures and characteristics* - test interval, test configuration, planned versus corrective maintenance strategy, maintenance configuration.

Two main topics were discussed:
- the strength of relation between the individual CCF coupling factors (contributing to total CCF potential) and ageing phenomena
- CCF prevention measures effect on the coupling factors versus ageing relation (estimated for those CCF coupling factors which were evaluated as coincident with ageing phenomena, with at least medium level of coincidence).

Results

The following organizations have participated to the investigation:
• Institute for Nuclear Research Pitesti (INR), Romania

• Nuclear Research Institute Rez (NRI), Czech Republic
• Cernavoda Nuclear Power Plant (CNPP), Romania
• National Agency for New Technologies, Energy and the Environment (ENEA), Italy

The participants provided answers to all questionnaire tables, all the inputs being developed in completely independent way. All these inputs were summarized, compared and commented.

All the coupling factors were discussed and some specific examples, from operating experience were given. Some developed remarks [4] and illustrative example for each coupling factor are given below.

For hardware based coupling factors:
▪ *same physical appearance*
For the components with significantly different physical appearance, connection of this factor with ageing may be seen as negligible. However, if there is some level of similarity, this may be further increased by ageing effects, because the specific features of the individual components may gradually disappear in the process of ageing (decreased readability of component identifiers, loss of identification elements etc.). During discussions, it was given as an illustrative example of this coupling factor the removal, from operation to maintenance, of other pumps than the one needed, due to the component misidentification.
▪ *system layout/ configuration*
In PSA model, this case refers to connection of formally separated components in higher level of system function logic. Any potential increasing of failure rate of this higher level component (if it is exposed to some ageing mechanisms) due to ageing can be seen as increasing of CCF potential. Wrong layout/configuration may results in high wear rate of a component category. *Example1: the failure of containment spray pumps to meet differential pressure requirements, due to air binding at the pump suction (resulting from a system piping design error). Example2: the failure of bearing of the pumps/motors shift – the RMZ (Zero Power Multi-zone Reactor main circulating pumps) due to design error - wrong position (the situation was identified at preoperational tests and the pumps were relocated).*
▪ *same component internal parts*
A common construction principle may represent a CCF failure potential increasing in time due to effects of ageing. The same type of component internal parts does belong to CCF factors with significant connection to ageing potential, when "same type of component internal parts" factor is accompanied by "same manufacturer" attribute. *Any part of I&C component, having impact on availability of same type components in several redundant trains of the system, can be seen as very good generic example.*
▪ *same maintenance/ test/ calibration characteristics*
One of the main maintenance goals is prevention of effects of known and expected-to-occur ageing mechanisms. Since the maintenance strategy principles are usually built in such a way that there are dependences and correlations in planning, organization and way of carrying out the individual maintenance activities for various types of components, there is some possibility that ageing mechanisms may not be addressed adequately not only for one, but for all components forming some CCF group in PSA model. *Example: the failure to load of two diesel generators due to shutdown sequencer problems. During one diesel generator failure, the diesel could not be loaded manually or automatically due to dirty contacts on the sequencer. In the second diesel failure, the sequencer clutch stuck due to being dirty and needing lubrication. The cause was determined to be the lack of quality of preventive maintenance.*
▪ *manufacturing attributes*
The "same manufacturer" factor overlaps, to some extent, with the "same internal parts" factor. The production quality is strongly determined by quality assurance principles taken into consideration during production, and ageing phenomena treatment may be seen as one of them. In case when these quality principles are deficient from ageing treatment point of view, component performance degradations may occur with high probability and the phenomena is likely to impact all group components.
▪ *construction/ installation attributes*
Some potential exists for latent effect of hidden impact of wrong equipment installation for a long time period and strengthening of it in interaction with ageing mechanisms, but such potential was considered as relatively weak.

For operation based coupling factors:
▪ *same operating team*
The actions of the same team could be a strong cause for occurrence of CCF failures. In time, the component potential to survive to the consequences of wrong activity of the same operational team, assuming the interference with ageing mechanisms is very small. Still, there are two side of the coin, since the typical ageing effects are developing during a relatively long time period, the operational team may be subjects to changes within, or they may gain experience and skills. *Example: All emergency service water pumps were found in tripped status, as the result of an emergency engine shutdown device being tripped. The operational personnel did not recognize that the trip devices has to be reset following testing.*
▪ *same operating procedure*
The influence of the same operational procedures was considered higher than the influence of the same team, because the changes in the content of procedures are usually smaller and less frequent than the changes in the operational team. As a consequence, accumulation of procedure negative effects may impact more strongly the components in a long period of time. *Example: Two auxiliary feed water pumps failed to develop the proper flow output. It was determined that the manual governor speed control knobs had been placed in the wrong position due to an error in the procedure.*
▪ *same maintenance/ test/ calibration team*
The influence of this factor is variable, tightly connected with the frequency of changes in the maintenance/ test/ calibration staff (which is given by plant human resources politics, including level of outsourcing and safety culture of external contractors, and can be different among the plants). In the operation of plants with relatively low staff fluctuation, the factor may be quite important, because the maintenance/test/calibration style may become loaded

with all kind of negative stereotypes, or the team may accumulate experience and become more skilled in performing their activities. *Example: A number of breakers in electric power supply system failed to close due to dirt and foreign material accumulation in breaker relays. Existing maintenance activities allowed the relays to be inoperable and not detected as inoperable until the time that the breakers were called-on to operate.*

▪ *same maintenance/ test/ calibration procedures*

For a number of important safety components, latent effects of a defective maintenance, cumulated and interfering with real ageing impacts may be stronger than the impact of operational problems, leading to initiation or strengthening of ageing mechanism impact. If maintenance strategy is deficient in some way, there is a quite real chance that undesirable effects will repeatedly take place during periodically performed maintenance activities, potentially contributing to ageing. *Example: activation of the high bearing temperature alarm of component cooling water pump. Investigation revealed that the pump bearing had rotated, blocking oil flow to the bearing; apparent cause was pump/ motor misalignment; 11 days later, the same symptoms appeared in operation of the other component cooling water pump.*

For environmental based coupling factors:

▪ *same plant location*

It implies similar impact of external environmental characteristics which define, to some extent, ageing potential. The impact of many environmental stresses (fire, flood) is normally modelled explicitly (by analysing the phenomena involved and incorporating their impact into the plant/ system models) in current PSA studies. Other environmental factors, such as high humidity and temperature fluctuations are typically considered in CCF analysis and treated parametrically. The factor may be seen as relatively important for most of the components. *Example: the common trip of components due to weather effects - freezing up in winter or overheating in summer.*

▪ *same component location*

A stressful location implies a number of negative influences challenging component status during the whole component life period. If these influences generate common cause failure potential, CCF vulnerability will gradually increase as a consequence of negative impacts accumulation. *Example: Both auxiliary feed water pumps were sprayed by stream of water from broken piping of service water system. As result, auxiliary feed water system was lost completely.*

▪ *internal environment/ working medium*

There is an intensive contact between internal environment and the component under concern, and the negative consequences may occur rapidly in a case of harsh internal environment. *Example: the failure of four of six service water pumps due to wear caused by high pump vibration. The pumps have suction on ocean, and the failures were caused by excessive quantities of abrasive particles in the ocean water.*

The estimations were made using a five-degree colour scheme, assigned to correspond to one of the following defined categories: week, medium-week, medium, medium-strong, strong. The scales was used to rank each coupling mechanisms and the strength of connection with ageing, and the influence of CCF prevention means on the links between CCF potential and ageing.

Most of the project participants provided samples of data describing CCF events from their own operational history, and illustrated the link between occurred CCF events and ageing phenomena, as the risk associated with selected events. Some examples are given in Table 1.

Table 1 - Sample of CCF events from point of view of relation to ageing phenomena (operational experience)

Event description	**Risk related impact**	**Relation to ageing**
Cernavoda NPP - The valves controlling the level in Steam Generators in emergency situation was found to have the seat for impulse air of pneumatic relay excessively worn.	Degraded function of boiler level control in emergency situation.	Probable link to ageing, event possible to be time dependent.
Cernavoda NPP - The valves controlling the level in Steam Generators in emergency situation was found to have failed PRV diaphragm.	Degraded function of boiler level control in emergency situation.	Proven link to ageing.
Cernavoda NPP - Ageing of wall pass-through insulation for both 110kV buses of Station A.	Degraded function of 110kV station to feed the plant internal services.	Proven link to ageing.
TRIGA secondary circuit – the valves bodies are corroded, do not seal anymore and cannot be operated	Improper operation of valves results in a reduced flow through the system which was detected by the increasing temperature in primary circuit.	Wear and erosion processes have as effects the walls thinning until leakage occurs. Corrosion phenomena can make the valve to operate with difficulty. The event was caused by ageing/inadequate maintenance.
TRIGA secondary circuit - pipes rupture - the underground and external pipes very corroded	Large breaks lead to harsh environment and flood with consequential failures of multiple equipment. Wall thinning and cracking are incipient failures, in time they could lead to external leaks.	Corrosion-erosion may result in pipe wall thinning which compromise the integrity of the piping and could result in external leakages. Event is caused by ageing.

The strength of connection of CCF coupling factors with ageing phenomena was estimated according to what has been found both in operational experience and theoretical studies, [4]. To better illustrate the estimations for connection strength between coupling factors and ageing phenomena, Figs 1 and 2 were developed. Estimations went from weak to strong impact, using a 5-degrees scale. Each group opinions were represented by a different colour.

Mean level of coupling factor coincidence with ageing was defined as "Impact", postulated on the base of estimators given by the participants groups.

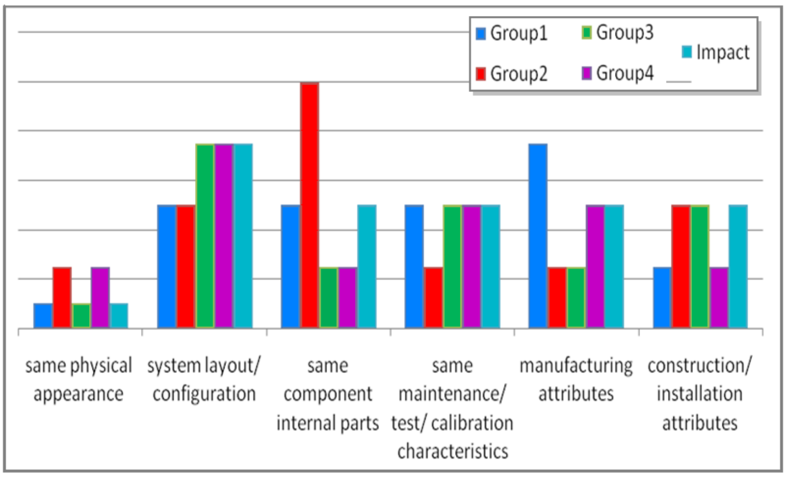

Fig. 1 Estimations for connection strength between hardware based coupling factors and ageing phenomena

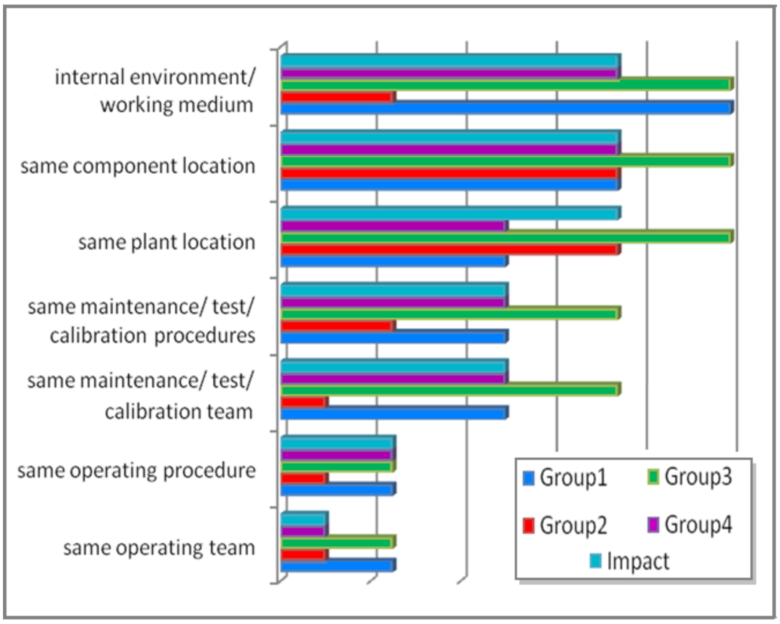

Fig. 2 Estimations for connection strength between operational/ environmental based coupling factors and ageing

The discussions revealed the following issues:

▪ All environmental based coupling factors were evaluated as relatively strong in connection to ageing; in case of same component location factor the estimations were made with very small variability of the individual estimates

▪ Same physical appearance and same operating staff were evaluated as having weak connection to ageing phenomena (with small variability of estimates).

The influence of CCF prevention measures on the strength of connection of CCF coupling mechanisms with ageing phenomena was estimated also according to operational experience and expert judgments.[4].

A summary of these estimations is given in Fig. 3. Mean level of influence of ageing on CCF prevention measures was defined as "Influence", postulated on the base of estimators given by the participants groups.

The discussions revealed the following:

▪ The CCF prevention strategies based on application of diversity principles were found as significantly breaking the link between CCF potential and ageing, much more than the remaining classes of prevention strategies

▪ Most of evaluated combinations of prevention strategy and CCF coupling factors-ageing links were evaluated as having medium influence

▪ Very good agreement in estimation of impact of prevention strategies based on diversity, they were evaluated as being really important by all participants.

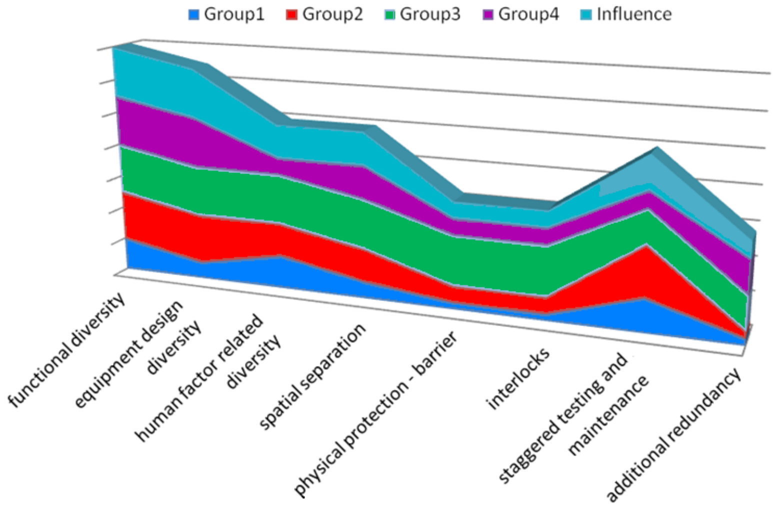

Fig. 3 Influence of CCF prevention means on the links between CCF potential and ageing

Conclusions

Detailed analysis of operational experience and comparison of the questionnaire answers provides evidence regarding non-negligible correlation between ageing phenomena and other factors that influence the potential for common cause failure occurrence.

Some component failure modes, which are sensitive to CCF potential, were revealed as a-priori candidates for ageing related analysis, as the following: plugging of (narrow) pipes, loss of piping system integrity, failure of cables insulation, failure to operate for switches. Corrosion factor can be seen implicitly as very important from point of view of CCF-ageing connection.

The following conclusions can be made based on the answers received to questionnaire and on the estimations:

▪ The relation between common cause failure potential represented by individual CCF coupling factors and ageing phenomena was estimated as fairly strong, both for total, summarized CCF potential, and for individual coupling factors. It should be mentioned that, in integrated opinions, the connection was never considered as irrelevant. As a direct consequence, CCF should constitute a specific item of the methodologies developed to treat the ageing phenomena effect in the PSA studies.

▪ The agreement among groups fulfilling the questionnaire might be considered as pretty good. The participants estimations were balanced regarding conservativeness level (no evaluator with too distant evaluations systematically made – over-optimistic or too pessimistic).

▪ Each of the four groups of CCF coupling factors was found as having at least medium importance regarding connection with ageing. The dominating group with respect to ageing is the one of environmental based factors, the coupling factors from this group could be prioritized for more detailed analysis.

▪ The level of subjectivity and corresponding level of variability of estimations was generally higher in case of combinations of prevention strategy and CCF coupling factors-ageing links than in the case of estimated CCF coupling factors versus ageing coincidence

▪ The factors that are increasing the CCF potential are relatively significantly tied with the factors that are increasing the components ageing potential. In some cases, the link between CCF and ageing can be identified easily (case of same component location), whereas deeper understanding of physical, technological, organizational processes during operation may be necessary in other cases (case of same maintenance staff).

In the future, it is intended to analyse much broader samples of operational experience and to perform more detailed analysis of available information about CCF events and their relation with ageing phenomena.

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